The Inner Sanctum of the Proton

Taking the closest look yet at this basic constituent of matter, an unusual new accelerator called HERA is finding that it has a surprisingly active inner life

The 1982 book *Powers of Ten* uses a series of images to take readers to the extremes of inner and outer space. Starting with a human-scale scene of a picnicking couple, the pictures pan out to encompass great arcs of galaxies, then zoom in on a hand, skin, cells, molecules, atoms, the atomic nucleus, and finally the proton. And that is where the tour cuts off: The best the book can offer for the interior of the proton is an abstract pattern of color symbolizing, as the narrator puts it, "the physics we just begin to comprehend." Now, more than 10 years later, the Hadron-Electron Ring Accelerator (HERA) at DESY, the German particle physics laboratory near Hamburg, is starting to penetrate this inner-space wilderness.

Before HERA, physicists already knew the proton's key constituents: three compact objects known as quarks. Quarks are so much smaller than the proton that they rattle around like a few grains of sand in a vast sea of space. That leaves a lot of room for other kinds of activity, but all physicists have had to understand what's there is a messy and poorly understood theory called quantum chromodynamics (QCD). The result was a mystery at the very heart of matter, because protons and neutrons, their close cousins, make up the bulk of the atom.

And that's where HERA comes in. In its first 2 years of operation, the collider has revealed that the proton—and by inference the neutron—has a surprisingly active inner life. "The more closely you probe, the more you see," says physicist Allen Caldwell of Columbia University. Caldwell and other members of HERA's international team of investigators have found, among other things, that the three familiar quarks are adrift in a surprisingly dense sea of short-lived "virtual" quarks that wink in and out of existence. And in a clue that there's still more to be learned, they have recorded mysterious collisions in which electrons ricochet off an unidentified object within the proton's inner space.

HERA owes its close-up vision more to a unique design than to sheer power. The facility's 850 billion electron volts of energy are modest next to the 2 trillion electron volts of the Fermi National Accelerator Laboratory's Tevatron. But HERA extracts considerable mileage from this modest energy by being the first facility to accelerate particles of wildly different masses: A beam of light, pointlike electrons circling the 6.8-kilometer ring in one direction collides with a beam of heavy, complex protons circling in the opposite direction. The beams interact in two detectors, Zeus and H1, located along the ring. When the electrons sideswipe the protons or strike them head-on, the electrons are deflected, and the protons explode in showers of particles. Both kinds of signals reveal clues to the proton's internal structure.

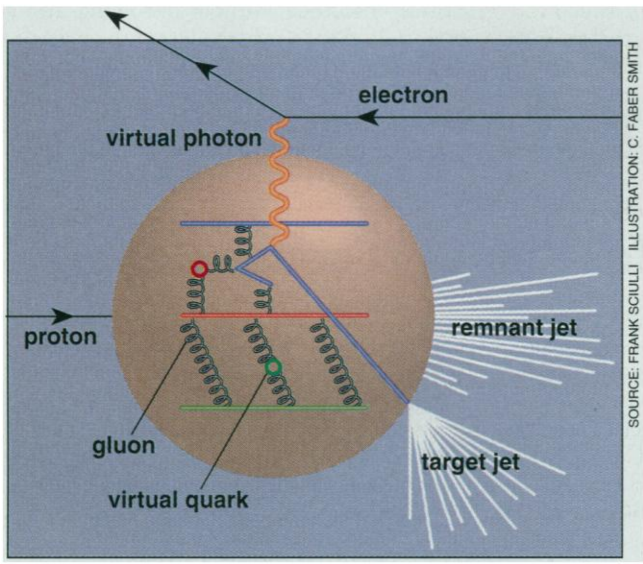
What happens within the two detectors is filling in a picture first glimpsed around 1970, when Jerome Friedman and Henry Kendall of the Massachusetts Institute of Technology and Richard Taylor of the Stanford Linear Accelerator Center shot electrons at protons in a fixed target. Most of the electrons sailed through the protons as if they weren't there, but a few rebounded off hard, pointlike objects that were later identified as quarks. In this Nobel prize–winning experiment, the proton appeared to contain just three of these kernels, now called "valence quarks." The valence quarks determine most of the properties of protons, just as valence electrons determine the important chemical properties of atoms.

That picture was a breakthrough, but it hasn't survived without some important modifications. Experiments in the late 1970s and early 1980s used more energetic electrons, which acted as finer probes (an electron can be thought of as a wave whose wavelength shrinks as its energy increases). These probes no longer passed through the proton oblivious to all but the valence quarks. Instead, they ricocheted off as if the proton contained four or five particles. "When you probe at smaller distances, you find there is much more structure," says Columbia theorist Alfred Mueller.

Virtual reality. The proliferating structure wasn't in itself surprising, since quantum mechanics implies that even the loneliest stretch of intergalactic vacuum is filled with short-lived "virtual" particles popping in and out of existence. In the interior of the proton, according to QCD, these virtual particles should take the form of quarks and a haze of force-carrying particles called gluons, which embody the force that binds quarks together. But although QCD is capable in principle of yielding a prediction for the number of these virtual particles inside the proton, the math is just too complicated, says Columbia physicist Frank Sciulli. "We don't have the smarts or the computing power to do it."

As a result, physicists were largely unprepared for the bustling crowd of virtual quarks and gluons HERA has revealed. By accelerating both protons and electrons and colliding them head-on, HERA achieves about 100 times the collision energy of the previous, fixed-target experiments, opening a window on a size scale 100 times smaller than has been available before.

Like earlier researchers working with fixed targets, Caldwell and his colleagues probe the structure of the proton by reading the post-collision trajectories of the electrons. But they also take advantage of additional clues: debris from smashed protons. Though virtual quarks come and go in a fraction of a second, a few last long enough to send an electron careening off course. In that process, the virtual quark gets knocked out of



Piercing the proton. An electron emits a virtual photon, which in this case ignores the three "valence" quarks (colored lines) and instead knocks out a virtual quark. Both the scattered quark and the proton then dissolve into jets of other particles.

the proton, causing the proton to fall apart. By recording the outcomes of thousands of collisions, HERA researchers can piece together a picture of a whole "sea" of virtual quarks and gluons and calculate its density. And in this picture, says Caldwell, "the proton's a very active beast."

So far, says DESY physicist Joel Feltesse, who leads the group running H1, the detectors see evidence for about 30 gluons and three or four virtual quarks at any given time. Because these numbers couldn't have been predicted from theory, says Columbia's Sciulli, they "will have a profound effect in the long run on our understanding of protons and neutrons." And Caldwell notes that HERA may also answer another open question: whether exotic quarks can make a fleeting appearance in everyday protons and neutrons. Only two of the six quark types, "up" and "down," ever show up as valence quarks, but QCD leaves open the possibility that others—"charm" and "strange" quarks, for instance—can pop up in the virtual sea for long enough to get knocked out by an electron. Because these quarks are more massive than up and down quarks, they would leave different signatures in HERA's detectors.

The unexpectedly dense virtual sea is just one of the surprises emerging at HERA. There's also an unidentified object whose existence is inferred from a strange set of collision tracks. Generally, collisions transform the proton into spectacular showers of other particles—a display predicted by QCD, which holds that the proton's three valence quarks have different "colors" (arbitrarily called red, green, and blue), analogous to the positive and negative charges of electromagnetism. The proton's mix of colors renders it neutral and therefore stable. When an electron ejects a quark from a proton, both the quark and the proton lose their color neutrality. And objects with net color, such as naked quarks, immediately "clothe" themselves by pulling other quarks from the vacuum. That conjuring process stirs up additional particles in a kind of chain reaction. As a result, electron-proton collisions usually result in two particle jets, one generated by the ejected quark, the other—aimed in the proton's direction of travel—by the proton fragment.

Mystery particle. In the collisions that are raising eyebrows, however, the electron seems to ricochet off something within the proton. Meanwhile a jet—sparser than the ones generated by the ejected quarks—suggests that something has been knocked out of the proton. Yet the proton seems to continue unscathed, without dissolving into a jet itself. Apparently the loss of the particle, whatever it is, doesn't upset the proton's color neutrality. "This was totally unexpected," says Caldwell.

Theorists' best guess so far about what the electron is hitting is a theoretical throwback called a pomeron. Invented in the early 1960s by the Russian theorist Isaac Pomeranchuk to explain early indications that the proton has internal anatomy, the pomeron was set aside later when quarks were identified as the proton's internal components. Says Argonne National Laboratory physicist Malcolm Derrick: "The nature of the pomeron has been a mystery for 30 years." Perhaps this new result will help unlock the mystery, he says.

Derrick and his colleagues think that, unlike the top quark, which recently catapulted Illinois' Fermilab into the headlines, the pomeron is not a new particle. It may be something more like a temporary lump in the soup—perhaps a temporary clump of gluons. But even a cluster of known particles would be a surprise, because nothing in established theory predicts such behavior.

And that's the excitement of HERA's exploration of inner space, say physicists; no one knows what else they might find in coming years, when they plan to amass 100 times more data than they have collected so far. For a field in which many recent experiments have simply explored territory that theorists have mapped, having experiment take the lead into the inner-space frontier is a welcome change. Says Derrick, "We're in uncharted territory."

–Faye Flam

GENETICS

Lucky Break for Kidney Disease Gene

By spotting a clue in the chromosomes of a Portuguese family, an international team of researchers has homed in on the cause of the most common inherited kidney disease. The researchers, led by geneticist Peter Harris of the Medical Research Council's Molecular Haematology Unit in Oxford, England, announce in the 17 June issue of *Cell* that they've identified the gene at fault in most cases of autosomal dominant polycystic kidney disease (ADPKD), in which fluid-filled cysts form in the kidneys, damaging or destroying them.

So far, the group knows part of the gene's DNA sequence but not how it works. As a result, they're a long way from being able to prevent or treat the disease, which afflicts about 1 person in every 1000 and, in half of the cases, ultimately requires dialysis or a kidney transplant. But other workers in the field are hailing the Oxford group's achievement, which entailed singling out the errant gene from a region on chromosome 16 containing over 20 suspect sequences. Says geneticist Steve Reeders of Harvard Medical School, "This is very exciting—we've been on [the trail of] this gene for 3 years but found it very difficult to find any mutations." Reeders adds, "All the data together make me convinced [this is the gene responsible]."

Reeders and his group had identified the approximate location of the ADPKD gene in 1985 by tracing the inheritance of genetic markers in afflicted families. But when various laboratories analyzed parts of the suspect chromosome region, they found a number of unknown genes, any one of which might have been at fault. In hopes of pinpointing the culprit, Harris's Oxford team, collaborating with scientists in Wales, Portugal, and the Netherlands, went hunting for visible abnormalities on chromosome 16 in ADPKD sufferers. A Portuguese family supplied the lucky break: In afflicted members of the family, part of chromosome 16 was swapped with a piece of chromosome 22.

By examining the DNA of ADPKD sufferers, the team was able to identify a large gene that was disrupted at the breakpoint on chromosome 16, making it the obvious candidate for being the gene at fault. With the gene sequence in hand, Harris's group examined the corresponding DNA in 300 more ADPKD families and identified three other mutations that can impair the gene, confirming its role in the disease.

The Harris group calls their prize *PKD1* (the 1 is an acknowledgement that another, as-yet-unidentified gene on chromosome 4 is responsible for perhaps 15% of ADPKD cases). Screening for *PKD1* mutations should ultimately make it possible to identify most people who will develop polycystic kidney disease, which usually becomes apparent in middle age. Doctors could then be vigilant for damaging symptoms, such as hypertension, that can be treated.

To understand the disease, however, the researchers will now have to learn what kind of protein *PKD1* encodes and what function it plays in the body, as well as how the mutations disrupt it. "We're not sure whether the mutation results in the absence of the protein or a defective product," says Harris, who adds that answering these questions is his next goal.

Reeders cautions that determining how *PKD1* works is likely to be"tough sledding," because the gene's unusual length will make it difficult to characterize. As other successful gene hunts have shown, finding a disease gene is only the first step toward a cure.

–Claire O'Brien

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